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Random Access to Mobile Networks with Advanced Error Correction

Michael Dippold
DLR, German Aerospace Research
Institute for Communications
D-8031 Weßling, F.R.G.
FAX ++8153 28243

ABSTRACT

A random access scheme for unreliable data channels is investigated in conjunction with an adaptive Hybrid-II ARQ scheme using RCPC codes FEC. A simple scheme with fixed frame length and equal slot sizes is chosen and reservation is implicit by the first packet transmitted randomly in a free slot, similar to Reservation Aloha. This allows the further transmission of redundancy if the last decoding attempt failed. Results show that a high channel utilization and superior throughput can be achieved with this scheme that shows a quite low implementation complexity. For the example of an interleaved Rayleigh channel and soft decision utilization and mean delay are calculated. An utilization of 40% may be achieved for a frame with the number of slots being equal to half the station number under high traffic load. The effects of feedback channel errors and some countermeasures are discussed.

I. INTRODUCTION

The efficiency of channel access techniques for mobile services is degraded by channel impairments like multipath propagation and shadowing. More complicated reservation schemes show a faster degradation than the simpler random access methods under these conditions. Many recent publications are devoted to this problem. For example the improved efficiency of Slotted Aloha through the capture effect was studied in [1] for a Rayleigh channel and in [2] for the landmobile satellite channel. In [3] the effect of capture with a tree collision resolution algorithm was analyzed for obstacles between transmitter and receiver. The performance of a reservation scheme was compared to that of Slotted Aloha in [4].

In most of the investigations it was assumed that a packet has to be repeated if the detection failed due to bit errors. This basicly is the mechanism of type-I or type-II hybrid ARQ (Automatic Repeat Request). However, especially for time varying channel quality like in mobile applications it has been shown that more effective schemes exist, e.g. [5]. Essentially they are based on the idea of successive parity transmission and usage of all the information of the previous unsuccessful decoding attempts. In general this increases the throughput between transmitter and receiver. The criterion of point-to-point throughput used in ARQ analysis is sometimes not useful in a multiuser environment in connection with random access. Here channel utilization is an usual measure of system quality.

We investigate the use of such an advanced Hybrid ARQ scheme in the random access multiuser application for mobile data transmission. It is applicable for bursty data transmission or random access reservations for a SCPC voice channel. Although access schemes with fixed slot sizes are better to implement and work more reliable, the adaptive hybrid ARQ methods perform best, if redundancy can be transmitted in very small portions. But also with equal packet sizes their main advantage is the use of all formerly transmitted data for an actual decoding attempt in the receiver. Because the receiver stores all the data received in unsuccessful detection attempts until an acknowledgement can be issued, even a one packet message becomes multiple packets in the case of packet errors.

For this reason we will regard an implicit reservation random access scheme instead of a pure Slotted Aloha technique. Details will be discussed in section 2. The ARQ scheme considered is based on the adaptive ARQ/FEC (Forward Error Correction) with RCPC-Codes and Viterbi decoding presented by Hagenauer in [6]. It is briefly reviewed in section III and a model for the combined performance of this method with the random access is presented. Section IV gives numerical results for the example of the Rayleigh fading channel.

II. RANDOM ACCESS WITH RESERVATION

The most effective way to use adaptive ARQ protocols is to allow arbitrary lengths of the various parity packets. However, variable slot size increases the complexity and hence network overhead and error possibilities of the access scheme. Therefore we consider only a fixed equal slot length. Slots are organized in a fixed size frame for the uplink from the mobile to the center (satellite). On the return link acknowledgements (ACK) and reservation confirmation are issued. The frame length exceeds the signal round trip time. Every station is allowed to transmit messages with variable length and hence variable packet number but may only use one slot per frame. Every packet is coded according to the coding rule and data and redundancy is stored for every packet until an ACK was received. We assume the following access algorithm:

On the return link for every data carrying slot a feedback is received unless a collision took place (it is reasonable to assume that the receiver distinguishes between collision and packet error with high probability). Any station to start transmission tries one not reserved slot. There are the following feedback signals (no feedback in the case of garbled data after a collision):

- Packet error and reservation for a further attempt ("RES")
- Acknowledgement for a successfully decoded packet and reservation for a next packet ("AR")
- Acknowledgement for the last packet and release of this slot ("ACK")

If Collision:	Try again in a free slot according to Slotted Aloha; no feedback.
If Success:	Done (1-packet message); feedback ACK. This slot is reserved in the next frame for the next packet (m-packet message); feedback AR.
If error:	Same slot in next frame reserved for transmission of additional redundancy; feedback RES.

Every packet carries an indicator whether more information packets are to follow or not. If decoding was not yet successful it is clear that more redundancy will be sent and hence the automatic reservation. This scheme is basicly the classical reservation Aloha introduced by [7] and is illustrated in Fig. 1. If all the priority is transmitted and decoding was not yet successful the station will try from the beginning and join the set of new arrivals. We do not consider code combining methods here.

Feedback Errors: We assume that no feedback error occurs as data may be protected by strong codes. However, there is a certain probability for landmobiles in the L-Band or shorter wavelength bands that shadowing occurs and no feedback signal is received.

- A station misses the AR or RES feedback: After its own transmission this leads to a new access attempt and the reserved slot is wasted. But if reservations for other stations are not heard, this may cause a collision, if the station tries a new access in this slot in the next frame. This problem is alleviated if the center transmits a reservation plan for the next frame. Only slots within a round trip time cannot be indicated.
- A station misses an ACK: If it was an ACK for its own transmission it keeps transmitting in a released slot. This also

can cause collision and the station is not informed about its own success. A collision indicator instead of no feedback in this case can be used. Missing ACK's for other stations means that the station in mind considers this slot as reserved although it has already been released.

All these errors result in a somewhat lower throughput and higher delay but should not be a problem if the probability for their appearance can be kept low.

Analysis

For the analysis we assume a stationary system with the following parameters:

F number of slots in every frame
H average number of packets per message including redundancy transmission
R average number of slots, which are reserved for transmission in a frame
M number of users in the system.

A station can only start its transmission by accessing a free slot. We model the complete system by a Markov-chain where the number of reserved slots in a frame is the state variable r. According to [8] we assume that all non-reserved F-r slots may be accessed in a Slotted Aloha manner with a channel utilization U_o. A station can hold only one reserved slot per frame. Any of the M-r stations not transmitting in the current frame starts transmission in the next frame with probability U_o. Any of the r active stations in the actual frame will have finished in the next frame with probability 1/H. The average message length H depends on the channel errors and will be calculated in the next section. In this model we can describe the probability that the number of reserved slots r is changed by i in the next slot

$(-r \leq i \leq F-r)$ by:

$$P_{r,\,r+i} = \sum_{l=0}^{r} \left[\binom{r}{l} (1/H)^{l} (1-1/H)^{r-l} \cdot \binom{M-r}{l+i} U_o^{\,l+i} (1-U_o)^{M-r-l-i} \right] \tag{1}$$

Solving the linear equation system

$$\begin{aligned} &\cdots \\ &P_r = p_{o,r} P_o + p_{1,r} P_1 \ldots + p_{F,r} P_F \\ &\cdots \qquad 0 \leq r \leq F \end{aligned} \tag{2}$$

we get the stationary probability distribution for the number of reserved slots with the mean value $R = E\{r\}$.

The channel utilization is the ratio of the average number of successful information packets per packet time. On the average m/H packets out of H are information, the other are redundancy. Related to the frame length F this results in:

$$U = \frac{R\, m/H}{F} \,. \tag{3}$$

The delay D for a message from the time a station starts to access the channel until an acknowledgement is received has several contributions:

$$D = D_1 + D_H + T_{RT} + 1.5 \tag{4}$$

D_1 is the delay until the first packet has been successfully placed into a slot, $D_H = (H-1)\,F$ is the time in slots until the last packet has been transmitted. Additionally after T_{RT}, the roundtrip time, an acknowledge can be received. For D_1 we assume that a station has to wait F/(F-R) slots on the average for a free slot, which is then accessed with a probability of success equal to U_S. As the whole system depends on the user activity an optimization would require a joint analysis of both the Slotted Aloha and the reservation system. It can be shown from the Markov analysis of Slotted Aloha, eg. [2] that the probability of success U_S for a station seeking access to the system is proportional to $(1-\sigma)^{-R}$, with σ being the arrival rate in a station in packets/slot. After K free slots on the average Slotted Aloha allows another attempt after a collision. Under the assumption of independent locations of free and reserved slots in a frame K free slots is equivalent to a period of $T_K = K\,F/(F-R)$ slots in total. Under these assumptions D_1

results in:

$$D_1 = \frac{F}{F-R} U_S + U_S(1-U_S)\, T_K + U_S(1-U_S)^2\, 2T_K + \ldots = \frac{F}{F-R}\, U_S + T_K\, \frac{1-U_S}{U_S} \qquad (5)$$

U_S indicates the probability that an access in the Slotted Aloha mode is successful (taken approximately equal both in the new arrival and repetition case here).

III. AVERAGE MESSAGE LENGTH

A message may consist of m packets each of length of one slot. Every packet is coded with the Punctured Convolutional Code of rate 1/N and stored in the transmitter. According to the scheme presented in [6] this results in m•N packets that may be transmitted at most. Decoding is performed after every packet and only if not successful the next portion is transmitted in the next frame. Due to the equal length constraint the coderate is decreasing in larger steps than necessary by the RCPC code alone. For example with the puncture period P a 1-packet message (m=1) exhibits the following successive coderates:
P/(P+P), P/(P+2P)..., P/(NP). However, for m > 1 a somewhat finer gradation can be allowed by interleaving the different information packets and their redundancy packets. But this must be known in the receiver. The superior performance of this adaptive scheme compared to conventional Hybrid-ARQ was recently shown in [9].

If we imagine the total coded message stored in n•m•P columns, the transmission proceeds in steps of ΔI additional columns after each decoding attempt. In the following we constrain ourselves to the case ΔI=P and m=1, where P is the puncture period. The average number of transmitted columns I_{AV} is then according to [6]:

$$I_{AV} = \sum_{k=1}^{N} kP\,(1-p_e(k\Delta I)) \prod_{i=0}^{k-1} p_e(i\Delta I) + N\,P \prod_{i=0}^{N} p_e(i\Delta I) \qquad (6)$$

With $p_e(k\Delta I)$ we express the probability that a packet cannot be decoded with kΔI columns of bits already received. Of course with $p_e=0$ in the error free case only P columns have to be transmitted and no additional redundancy is required.

In the transmitter a buffer capacity of m•N•Lp bits is required for a m-packet message. The demand for buffer is more critical in the receiver as in the extreme case (all slots reserved, all stations transmit full code) it increases with the frame length F: N•m•Lp•F. On the average only m•H•R•Lp bits of buffer are needed. An overflow would lead to a loss of already received information and will only effect U and D. Therefore a tradeoff between buffer space and utilization and delay is possible.

IV RESULTS

For the numerical evaluation of eq. 6 a Rayleigh channel with perfect channel state estimation and soft decision is chosen as an example. The packet error probability p_e was calculated using the figures in [6]. With $p_e(P)=1$ (certain packet error after the first transmission) the average message length $H = I_{AV}/P$ approaches H = 2 for large E_s/N_o. The dependence of H on E_s/N_o is shown in fig. 2. However, an inner code with some error correction facility instead of a CRC in the first packet would reduce $p_e(P)$ below 1 and H below 2 for the price of some additional redundancy. For comparison the mean message length H is also drawn in fig. 2 for the case ΔI=2. The advantage of a transmission of redundancy in smaller units than P becomes beneficial for higher E_s/N_o as the coderate may be decreased in finer steps. This would be possible in point-to-point connections or with unequal slot sizes in a multiaccess scheme. The following examples show the performance of the model from section II for the following figures: user activity per station $\sigma = 0.01$ messages/slot, operation point of Slotted Aloha $U_0 = 0.33$, number of stations $M = 30$, round trip time $T_{RT} = 2.4$ slots, no feedback errors. In Fig. 3 the channel utilization and the delay as function of the mean number of packets H are depicted (fixed frame length $F = 20$, number of packets per uncoded message $m = 1$). The delay D increases about linear with H, while the channel utilization U decreases. For higher m the utilization would be improved for a given H as is typical for reservation schemes.

A sensitive design parameter of the multiple access scheme described is the frame length. It has to be optimized in dependence of the number of stations M, the user activity σ and the channel quality (represented by H). Fig. 4 illustrates the mean delay D and channel utilization U as a function of the number of slots/frame F. For longer frames U decreases as too many slots stay idle. But with higher utilization the delay increases to infinity as all slots are reserved and new arrivals are blocked. With very high F the delay becomes larger again, as it takes H frames until a message is completed. However, long frames in the order of M are not sensible as fixed TDMA would be simpler and free of collisions.

V CONCLUSIONS

It has been shown that adaptive Hybrid ARQ schemes can be utilized in multiaccess environments. An implicit reservation scheme was chosen that is relatively simple to implement. Channel utilization and expected delay were calculated for the hybrid ARQ/FEC error correction with RCPC codes on a Rayleigh fading channel. The effectiveness of the adaptive ARQ is somewhat reduced by the constraint of equal size slots in the multiple access scheme. However, this disadvantage can be alleviated by the use of a high rate error correcting inner code in the hybrid ARQ scheme, or by reducing slot size to achieve multiple packets per uncoded message. The frame length is an important design parameter. Its influence on utilization and delay has been investigated. Further optimization of the combined adaptive ARQ and multiaccess scheme is required with respect to slot size, user activity and different channel characteristics.

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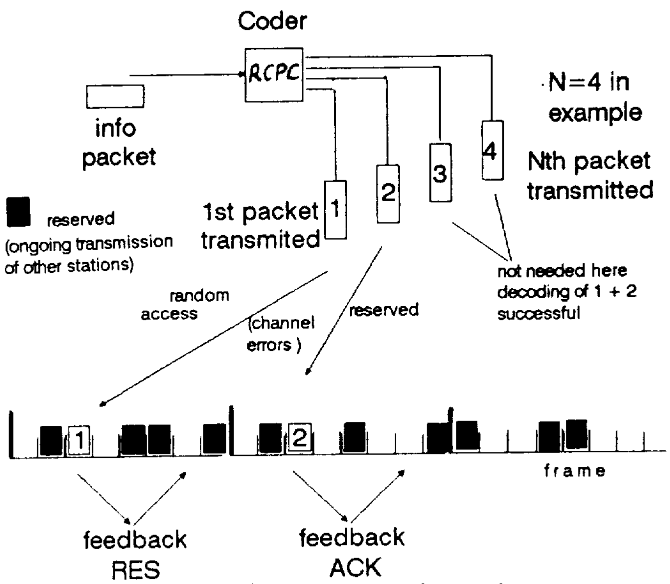

Fig. 1: Implicit reservation scheme

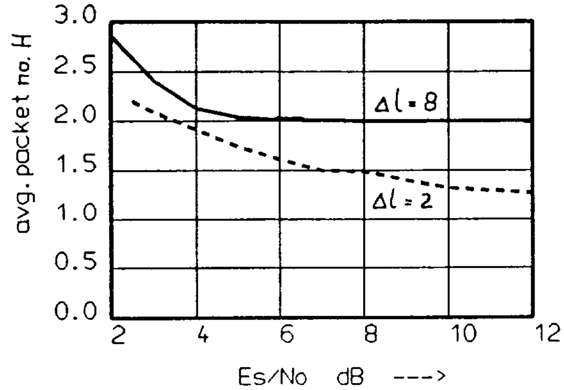

Fig. 2: Mean message length in packets (m=1, Rayleigh channel, soft decision, RCPC-Code N=4, P=8).

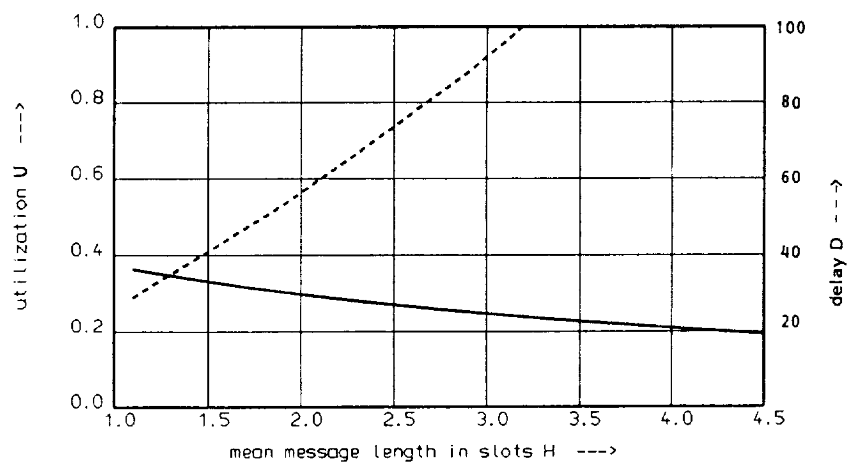

Fig. 3: Channel utilization U and delay D vs. mean message length H (M=30, F=20).

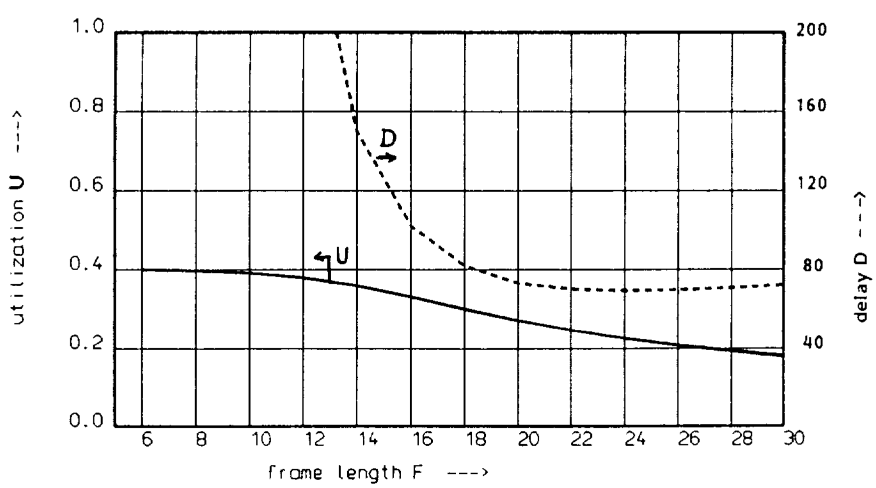

Fig. 4: Channel utilization U and delay D vs. frame length F (M=30, H=2.5).